Does synaesthesia protect against age-related memory loss?

Article (Accepted Version)

Does synaesthesia protect against age-related memory loss?

Abstract

Synaesthesia is known to be linked to enhanced episodic memory abilities, across a variety of stimuli and tests, but the evidence has tended to come from younger adults. This enhanced cognitive ability in early adult life, together with the known brain-related differences linked to synaesthesia (e.g., in both grey and white matter structure), makes it an ideal candidate for exploring the notion of 'reserve'. That is, synaesthetes may be able to utilise additional cognitive and/or neural resources to mitigate against the effects of age-related decline. This was explored in a 2x2 design contrasting age (young, old) against presence/absence of synaesthesia in two different studies: recognition memory for digits, snowflakes and music; and visual associative learning. Synaesthesia and age had independent, non-interacting, effects on memory ability suggesting that, whilst synaesthetes show a memory advantage and maintain this advantage in later life, the presence of synaesthesia is not able to act as a reserve to protect against the effects of ageing. On our tasks, the benefit of having synaesthesia (enhancing memory) was of a similar magnitude to the effects of age (impairing memory); in other words, elderly synaesthetes present with 'youthful' memory abilities. It is important for future research on elderly cohorts to consider the presence of synaesthesia as an individual difference.

Keywords: aging/ageing, synaesthesia/synesthesia, memory, cognitive reserve, brain reserve.

Introduction

Long-term memory, notably episodic memory, is a cognitive function that shows a particularly strong pattern of age-related cognitive decline (Ronnlund, Nyberg, Backman, & Nilsson, 2005). Whilst a significant body of research is dedicated to understand pathological aspects of aging (such as dementia), an important complementary approach considers factors that protect against cognitive decline. Nyberg et al. (2012) refers to this as 'brain maintenance' in as much as "individual differences in the manifestation of age-related brain changes and pathology allow some people to show little or no age-related cognitive decline" (pg. 295). This is related to theories of 'cognitive reserve' (Stern, 2009) or 'brain reserve' (Satz, 1993) which emphasise, to varying degrees, the extent to which an individual can actively (e.g. through strategic means, or compensatory mechanisms) or passively (e.g. through redundant capacity) utilise certain resources that may be less available in other individuals. Those individuals with greater reserve would be expected to show, at least in the early stages of aging, a shallower (or non-existent) decline in memory functioning because they can draw on their reserve before compromising essential functioning. This advantage has been linked to a variety of factors including lifestyle (Hultsch, Hertzog, Small, & Dixon, 1999), education (Hall et al., 2007), hippocampal volume (Persson et al., 2012), and genetic differences (Finkel, Reynolds, McArdle, & Pedersen, 2005). In the present study, we extend this research to consider synaesthesia. We propose that the neurocognitive profile of younger people with synaesthesia is consistent with existing notions of reserve and – hence – we test the hypothesis that older synaesthetes might show less age-related memory differences.

People with synaesthesia have atypical perceptual experiences (e.g. tastes or colours) that are elicited by unusual stimuli (e.g., listening to music), and these occur involuntarily and tend to be reliable over time (e.g., Ward, 2013). The developmental form of synaesthesia emerges in childhood (if not before) (Simner, Harrold, Creed, Monro, & Foulkes, 2009) and has a likely genetic component (e.g., Asher et al., 2009). The most commonly studied variant is termed grapheme-colour synaesthesia in which (written and /or spoken) letters or numbers trigger colours. These colours are experienced in the mind's eye or are externally projected perhaps as a type of strong mental imagery. Words tend to be coloured by the constituent letters and multi-digit numbers by the constituent numbers (e.g., Simner, Glover & Mowat, 2006). The brains of grapheme-colour synaesthetes show a number of unusual structural differences. These include increases in grey matter volume (assessed via Voxel-Based Morphometry) in regions such as superior parietal cortex, hippocampus, and fusiform gyrus (Rouw & Scholte, 2010; Weiss & Fink, 2009); and increased white matter organisation (assessed using Diffusion Tensor Imaging) in regions such as frontal, parietal and infero-temporal cortex (Rouw & Scholte, 2007). Both of these structural features are elsewhere frequently cited as candidates for 'brain reserve' which might limit age-related decline (Barulli & Stern, 2013; Nyberg et al., 2012). Grapheme-colour synaesthetes also have an interesting profile of cognitive abilities which have been most extensively studied in the domain of memory. These synaesthetes have shown enhanced long-term memory on many laboratory tests, typically with medium effect sizes (Rothen, Meier, & Ward, 2012). It is important to note that the memory enhancement is not necessarily limited to stimuli that induce synaesthesia (e.g. words). Indeed, one of the largest studies to date found that the visual memory abilities of synaesthetes exceeded their verbal memory (Rothen & Meier, 2010). Moreover, the memory advantage of synaesthetes occurs irrespective of the strategy used, and can occur for stimuli that are not readily amenable to mnemonic strategies such as images of fractals (Ward, Hovard, Jones, & Rothen, 2013; or snowflakes, as we use here). As such, we conclude that the memory advantage of synaesthetes is genuine - i.e. reflects ability rather than effort (Rothen et al., 2012).

The synaesthesia research discussed above was primarily conducted on younger participants. Those studies that did happen to include older people did not stratify the results by age. Little is known about how synaesthesia interacts with age (but see Meier, Rothen, & Walter, 2014; Simner, Ipser, Smees, & Alvarez 2017), so we address this here by studying the memory abilities of younger and older synaesthetes. Our study employs a cross-sectional, rather than longitudinal design. As such, we are measuring age-related cognitive differences rather than decline in real-time. Our experimental hypothesis, as articulated above, is that synaesthesia will protect against cognitive decline which we term the 'strong protection' hypothesis. In this view, older synaesthetes will resemble younger synaesthetes more than older controls,. This would manifest itself as an interaction between synaesthesia and age and would be consistent with the 'reserve' notion that higher functioning earlier in life protects against age-related decline. The null hypothesis is that there will be no protective effect. This could manifest itself either as a normal decline or even accelerated decline, as depicted in Figure 1. A normal rate of decline would manifest itself as an additive effects of age and synaesthesia. Note here that older synaesthetes could most closely resemble younger controls. This we term the 'maintain advantage' hypothesis. Theoretically, this would show that the boost given by the presence of synaesthesia is not able to act as a reserve, and would perhaps indicate that different neural/cognitive mechanisms support age-related memory and synaesthesia-related memory. Finally, it is possible that the presence of synaesthesia only boosts memory in younger people, not older people. This would also be revealed by an age X synaesthesia interaction. Here, older synaesthetes would most closely resemble older controls. We term this the 'burn-out' hypothesis. This is the least expected outcome, although it is to be noted that one genetic variant linked to Alzheimer's may convey cognitive enhancement only in younger people (Marchant, King, Tabet, & Rusted, 2010).

INSERT FIGURE 1 ABOUT HERE

Our choice of experimental methods to assess memory was motivated by several considerations. Firstly, they were chosen to be difficult and unlikely to generate ceiling (or floor) effects. Second, and relatedly, they used unfamiliar material to minimise effects of prior expertise and to minimise use of obvious mnemonic strategies (which are in turn related to factors such as IQ and education rather than memory ability per se; Garrett, Grady, & Hasher, 2010). For instance, our first study requires participants to remember images of snowflakes, which is based on previous research showing that people who successfully compete in memory tournaments do not perform better than the general population on this measure (Maguire, Valentine, Wilding, & Kapur, 2003). Finally, our tasks are taken from, or related to, others that have shown a memory advantage for younger synaesthetes (e.g., in Experiment 2, taken from Pritchard, Rothen, Coolbear, & Ward, 2013).

Experiment 1

Experiment 1 is an old/new recognition memory test, with confidence judgments, for digits, images of snowflakes, and musical passages.

Methods

Participants

Our participants were adult grapheme-colour synaesthetes in two age groups (younger and older) plus non-synaesthete controls. Table 1 contains the demographic information of our participants. Age differences formed two discrete bands (18-30 years, and 55+ years) rather than being continuous. Synaesthete participants were recruited from a database of volunteers hosted by our research group, and older control participants were recruited from a second database of non-synaesthetes. Younger controls were recruited from the University of XXX community. The study was approved by the Sciences and Technology Cross-Schools Research Ethics Committee at the University of XXX.

Grapheme-colour synaesthetes were validated as genuine synaesthetes having previously completed a standardised test of synaesthesia hosted at www.synesthete.org (for detailed methods see Eagleman et al., 2007), although data from one synaesthete was missing. This test detects the behavioural 'gold standard' feature of synaesthesia which is very high consistency when repeatedly reporting synaesthetic associations. (In this task, a set of 36 letters and single digits are presented on three occasions and participants select from an RGB colour palette. Small differences in colour space, within items, indicate high consistency, such that a consistency score below 1.43 is indicative of grapheme-colour synaesthesia; Rothen, Seth, Witzel & Ward, 2013. All of our synaesthetes scored the required < 1.43; $M = 0.69$, $SD = 0.19$).

INSERT TABLE 1 ABOUT HERE

The older synaesthete and older control groups did not differ in terms of age, $t(44) = 1.50$, $p = .140$. The same was true of the younger synaesthete and younger control groups ($t(50) = 0.37$, $p = .713$). Because one component of our test would assess memory for music, we requested participants' self-reported level of musical expertise on a 3-point scale (see below). Chi-squared tests revealed no significant difference in musical expertise according to age in the synaesthete ($\chi2 = 0.03$, $df = 2$, $p = .985$) or control group ($\chi2 = 4.03$, $df = 2$, $p = .133$).

Materials

We selected memory stimuli from three different modalities: three-digit numbers, images of snowflakes, and short musical passages. For the former, we used a random number generator to create a list of random numbers between 100 and 999. These were presented centrally on-screen in Arial font, point size 100. Snowflake images were taken from the digital archive of the photographer Wilson Bentley (http://snowflakebentley.com). All images were greyscale. Stimulus size was approximately 460 x 440 pixels and presentation was centrally on-screen. Musical stimuli were recorded using the digital audio workstation Logic Pro X. Each phrase contained 6 notes and lasted 4 seconds, with each musical sample playing for two bars of 4/4 time signature. All phrases were written diatonically in key signatures that varied from item to item. There was a range of articulation used, such as legato and staccato, and also a mixture of short and long duration notes. The notes were all between two octaves, the lowest being G below middle C and the highest being G two octaves above middle C. An example of a musical phrase is given in musical notation in Figure S1 in Supplementary Materials.

A set of 60 items was generated for each of these modalities. These sets were split into two lists of 30. For half of the participants, one list was used as target stimuli ('old' items, hence these were also learning stimuli) and the other as lure stimuli ('new' items). For the other half of the participants, the designated target and lure stimuli were reversed.

Procedure

Participants were tested online using Inquisit 4 software (www.millisecond.com) or Java software (both versions of the task functioned identically). Participants first completed a consent page and entered their demographic and musical experience information (which we coded as little/no musical experience, intermediate level, expert levelpoint scale) before the task began. During this time, a sound check file played and participants were warned that if they could not hear the sound, they should abort the task and check the sound settings on their computer before re-starting the task.

The order in which modalities were presented was randomised between participants. The testing phase for each modality immediately followed training on that modality. Thus participants fully completed one modality before proceeding to the next. The order in which stimuli were presented within the training and testing phases was randomised between participants. At the start of each training phase participants were informed of the modality, and that they should try to memorise the presented stimuli. During the training phases, stimuli were presented sequentially. Digits and snowflakes were presented for 2500 ms, with an inter-trial duration of 500 ms. Music stimuli were presented for their full duration, with an inter-trial interval of 2 s (pilot testing suggested a shorter inter-trial interval resulted in difficulty discerning individual musical passages). While the musical stimuli were playing, an image of a crotchet (quarter note) appeared on-screen.

At the start of each testing phase participants were informed they would be presented with another set of stimuli of the same modality as those just encountered in the training phase. They were informed that some of these they had encountered previously (‘old’) and some they had not (‘new’), and their task was to decide whether each stimulus was old or new, and that they should also indicate their confidence in each judgement. They were also informed of the response keys. If they thought the item was old and they had confidence, they should press X. If they thought the item was old and they were not confident they should press C. If they thought the item was new and they had confidence they should press M. If they thought the item was new and they were not confident they should press N.

During the testing phases again stimuli were presented sequentially, centrally on-screen. The response keys were displayed in the bottom quarter of the screen. For each stimulus, participants gave their old/new judgement and indicated their confidence in that judgement. Responses were unspeeded, and visually presented stimuli remained on-screen until a response was given (music stimuli only played once). There was a 500 ms interval between trials. The experiment ended with a debriefing after completing all three modalities.

Results and Discussion

The results are summarised in Figure 2 (collapsing across modalities) and Table 2 (uncollapsed). Considering the overall performance measured by d-prime, a mixed 2x2x3 ANOVA contrasting age, presence of synaesthesia and modality of stimulus was performed. There were significant effects of age ($F(1,94) = 10.024$, $p = .002$, $\eta 2 = .096$) and synaesthesia ($F(1,94) = 16.525$, $p <.001$, $\eta 2 = .150$) but no interaction between them ($F(1,94) = 0.646$, $p = .424$, $\eta 2 = .007$). There was a main effect of modality ($F(2,188) = 8.954$, $p < .001$, $\eta 2 = .087$) and a modality X age interaction ($F(1,188) = 12.960$, $p <.001$, $\eta 2 = .121$), with the musical stimuli showing the largest age-related loss. No other interactions were significant ($p > .1$).

INSERT FIGURE 2 ABOUT HERE

INSERT TABLE 2 ABOUT HERE

The absence of a significant interaction between age and synaesthesia was explored further by calculating Bayes factors (BFs) using the BF_t script (Weins, 2017). A Bayes factor enables estimation of the probability of a null hypothesis against a pre-defined theory. The protective effect theory makes the assumption that older synaesthetes will be equivalent to younger synaesthete (so the expected size of the interaction can be calculated from that assumption), whereas the burn-out hypothesis assumes that older synaesthetes will be equivalent to older controls. The prior was modelled on a two-tailed normal distribution with mean (m) and SD of m/2 such that the expected data would lie between 0 and 2m (Dienes, 2014). A value of BF<.33 is conventionally taken as sufficiently sensitive evidence in favour of the null hypothesis over the theory, while a value between .33 and 1 is taken as anecdotal evidence in the same direction (and ≥1 is taken as *no* evidence for the null; Jeffreys, 1961). The BFs for protective effect and burn-out were 0.25 and 0.53 respectively, which provides evidence against the protective effects theory and suggestive/anecdotal evidence against burn-out.

In a second analysis we considered not only accuracy but also our participants' confidence when replying (Table 3). When considering responses that were correct and confident, we found largely the same overall pattern, although the ageing and synaesthesia effects were more pronounced while the effect of modality became non-significant (age: $F(1,94) = 13.965$, $p < .001$, $\eta 2 = .129$; synaesthesia: $F(1,94) = 16.703$, $p <.001$, $\eta 2=.151$; age X synaesthesia: $F(1,94) = 0.650$, $p = .422$, $\eta 2 = .007$; modality: $F(2,188) = 1.765$, $p = .174$, $\eta 2 = .018$; age X modality: $F(2,188) = 5.797$, $p = .004$, $\eta 2 = .058$; other p's > .1). The Bayes Factor supported the null (maintain advantage) relative to protective effects (BF=.21), and provided suggestive evidence for the null relative to burn-out (BF=.51). In terms of synaesthesia, the effect sizes for the synaesthetic memory advantage within each age group and modality ranged from .32 to .74 (Cohen's d) when considering overall accuracy, but ranged from .65 to 1.15 when considering accurate and confident responses (see Table S1 in Supplementary Results). We interpret the greater tendency for synaesthetes to be both confident and accurate in terms of the high quality and strength of accurate memory representations linked to synaesthesia. It does not reflect a tendency to be confident per se (i.e. over-confidence) because neither synaesthetes nor younger people show an increased tendency to respond confidently on incorrect trials (a 2x2x3 ANOVA on incorrect confident trials revealed only a main effect of modality, $F(2,188) = 6.070$, $p = .003$, $\eta 2 = .061$; all other p's > .100).

INSERT TABLE 3 ABOUT HERE

Adding musical expertise as a covariate had a significant effect on memory for music but not for the digits or snowflakes (here we report the effect of the musical expertise covariate on d-prime in separate 2x2 ANOVAs contrasting age and synaesthesia: effect of covariate were music $F(1,90) = 6.279$, $p = .010$; snowflakes $F(1,90) = 0.448$, $p = .505$; digits $F(1,90) = 0.040$, $p = .842$). As such, an important secondary finding is that being an expert in the domain of music does not generate a cognitive reserve to reduce the impact of older age on musical memory (this is shown graphically in the Figure S2 in Supplementary Materials).

In summary, our results show for the first time that synaesthesia is linked to enhanced memory throughout the lifespan and not just in younger people. We also replicate previous results showing that the memory advantage of synaesthetes is not limited to synaesthetic inducers (in this case, digits were the only materials that were also inducers; snowflakes and music were not). However, there is no evidence that the enhanced memory of younger synaesthetes acts as a reserve to mitigate the effects of age-related memory deterioration (which would have predicted an age X synaesthesia interaction according to the 'strong protection' hypothesis). The data is consistent with the idea that older synaesthetes decline at a similar rate but start at a higher level of function, in-line with the 'maintain advantage' hypothesis (with the obvious caveat that we are estimating decline indirectly given the cross-sectional nature of the study). At least on this task, the memory advantage conferred to younger synaesthetes is numerically similar to the age-related memory disadvantage: the net effect being that older synaesthetes perform at a similar level to younger neurotypical controls.

Experiment 2

In our task (following Pritchard et al., 2013), participants must remember objects that have shape, colour and location, with these features individually varying between learning phase and testing phase.

Methods

Participants

We recruited a total of 136 participants in Experiment 2 who were crossed by age (younger=18-30 years; older = over 55 years) and synaesthesia status (grapheme-colour synaesthetes, non-synaesthetes), see Table 4 for demographic information. A subset of our participants' data was taken from a previously published study (Pritchard et al., 2013). Hence of our current subjects, the following numbers were taken from Pritchard et al.: 6/18 older synaesthetes, 3/21 older controls, 10/18 younger synaesthetes, 33/84 younger controls. Remaining participants were recruited in the same manner as Experiment 1.

INSERT TABLE 4 ABOUT HERE

As in Experiment 1, synaesthetes were confirmed as genuine with the conventional required consistency score of < 1.43 ($M = 0.66$, $SD = 0.22$; scores not available for 3). And as before, the older synaesthete and control groups did not differ in terms of age ($t(37) = 1.12$, $p = .269$) and same was true for the younger synaesthete and control groups ($t(100) = 1.33$, $p = .188$). There was no significant difference in education according to age in the synaesthete ($\chi2 = 2.58$, $df = 2$, $p = .275$) or control group ($\chi2 = 2.94$, $df = 2$, $p = .230$). We introduced a demographic question on education to check for any possible but unknown confounds of education not considered in Experiment 1.

Materials

The materials were the same as those used in Pritchard et al, (2013) and consisted of 40 stimuli: 10 targets and 30 distractors. Each stimulus was a conjunction of three features: a shape, a colour, and a location (on a 5x2 grid). Shapes were abstract forms designed to be distinct from each other visually and not resemble any common shapes or objects. Colours were exemplars of typical colour categories (red, orange, yellow, green, light blue, navy blue, purple, pink, grey, black). Targets were created by randomly combining, without replacement, a shape, colour and location. Thirty distractor stimuli were also created in which one feature was swapped with respect to a target. For example, if a target was a green shape in the top left cell of the 5x2 grid, a distractor was the same shape and location but in a different colour (e.g., red). Thus distracters varied from targets only on one dimension. The 30 distractors were split into three lists of 10, with one set having a changed colour, the next having a changed shape and the other a changed location. The same set of targets and distractors were used for all participants.

Procedure

Participants were tested online. Stimuli were presented using Adobe Flash or Qualtrics software (both versions of the task functioned identically). The task consisted of four identical blocks with each block consisting of a learning phase and a testing phase. After providing consent and demographic information, participants were instructed that they would be presented with a grid, and should remember the particular shapes along with their colours and locations. When ready, the first learning phase began. The 5 x 2 grid appeared on-screen and remained throughout the experiment. The ten target stimuli appeared on the screen sequentially, remaining for 3 s (there was no delay between trials). In the testing phase both targets and distractors were presented in a random order. Participants were informed that they should indicate whether these were exactly the same as those seen during learning or not. In this way our task was an ‘old/ new’ task as in Experiment 1, but this time participants responded with ‘correct’ (i.e., old) or ‘incorrect’ (i.e., new). Stimuli remained on-screen until a response was given. After the testing phase, the next block began again with the learning phase until all four blocks were completes. Presentation order was randomised within each learning phase, testing phase and between participants. Once the test had been completed participants gave their highest level of achieved formal education (school level, undergraduate degree received, postgraduate degree received).

INSERT FIGURE 3 ABOUT HERE

Results and Discussion

Firstly we consider overall performance in terms of d-prime (see Figure 4). A 2x2 ANOVA revealed a significant main effect of synaesthesia ($F(1,137) = 4.657$, $p = .033$, $\eta 2 = .033$), where synaesthetes out-performed non-synaesthetes. There was also a significant main effect of age ($F(1,137) = 6.164$, $p = .014$, $\eta 2 = .043$), where younger people out-performed younger people. As in Experiment 1, synaesthesia and age did not interact ($F(1,137) = 0.319$, $p = .573$, $\eta 2 = .002$). Calculation of Bayes factors, similarly to Experiment 1, provides suggestive evidence in favour of the null hypothesis when compared against the protective effect hypothesis (BF=0.41; i.e. based on the assumption that older synaesthetes would be like younger synaesthetes) and also compared against the burn-out hypothesis (BF=0.71; i.e. based on the assumption that older synaesthetes would be like older controls).

INSERT FIGURE 4 ABOUT HERE

Considering the three kinds of association, d-prime was again used as a measure to contrast stimulus type (colour, shape, location), group, and age as a 3x2x2 mixed ANOVA. The relevant descriptive statistics are shown in Table 5. As expected from the preceding analysis, the main effects of age ($F(1,137) = 9.780$, $p =.002$, $\eta 2 = .067$) and synaesthesia ($F(1,137) = 8.015$, $p =.005$, $\eta 2 = .055$) were significant but the interaction between them was not ($F(1,137) = .875$, $p =.351$, $\eta 2 = .006$). In addition, the effect of stimulus was significant ($F(2,274) = 75.592$, $p <.001$, $\eta 2 = .346$), and there were interactions between stimulus and age

($F(2,274) = 4.277$, $p = .022$, $\eta2 = .030$) and between stimulus and synaesthesia ($F(2,274) = 3.407$, $p = .035$, $\eta2 = .024$), but the triple interaction was not significant ($F(2,274) = 1.627$, $p = .198$, $\eta2 = .012$). These interactions were driven by performance on the 'shape change' stimuli which showed a stronger age-related differences (relative to the other stimuli) but was no different for synaesthetes versus controls. The 'colour change' stimuli showed the largest main effects of both synaesthesia and age and, as such, is the best candidate for exploring the specific theories outlined. Bayes factors contrasting the interaction term with those predicted from protective effects and burn-out were 0.26 and 1.01 respectively. Thus, there is strong support for the null hypothesis relative to protective effects, but the evidence is equivocal with regards to burn-out (note: BF=1 implies that the null and theory are equally probable).

INSERT TABLE 5 ABOUT HERE

It is also important to note that performance on the present task was not significantly affected by education level. Participants were grouped according to their highest level of formal education (School level N = 22; Undergraduate level N = 71; Postgraduate level N = 47). This has no effect on overall performance (2.04, 2.01, and 2.11 d-prime respectively; one-way ANOVA, $F(2,137) = 0.188$, $p = .829$, $\eta2 = .003$) or when entered as a covariate alongside the other variables (all p's>.1).

.

General Discussion

We have conducted the first study that directly examines the relationship between synaesthesia (which enhances memory) and ageing (which impairs memory) on tests of episodic memory. How might these two opposing influences affect performance in elderly synaesthetes? We hypothesized that the known cognitive abilities of younger synaesthetes (enhanced episodic memory), together with the associated brain-related differences (increased grey matter density and white matter organisation), are compatible with contemporary notions of ‘reserve’ in the ageing literature (Barulli & Stern, 2013; Nyberg et al., 2012). That is, the ability of certain individuals to draw on additional cognitive/neural resources to mitigate the effects of age-related cognitive decline (the ‘strong protection’ hypothesis). This would manifest itself as an interaction between age and synaesthesia in which older synaesthetes decline in performance at a slower rate than older controls. We found no evidence for this interaction in two studies presenting a wide variety of stimuli and memory measures. Both studies showed age-related main effects (albeit greater for some stimuli than others) making them suitable candidates to explore this hypothesis. In fact, Bayesian analyses showed support for the null hypothesis (i.e. maintain advantage) over the strong protection hypothesis. With regards to a third hypothesis - ‘burn out’ in which synaesthetes lose their initial advantage as they age - the results were insensitive but suggestive of the null (i.e. additive effects / maintain advantage). In summary, synaesthesia cannot act as a reserve to mitigate against aging.

It is important to note that this research does not provide evidence against the notion of reserve more broadly, for which there is strong evidence (e.g., Nyberg et al., 2012). It does, however, raise questions about how the concept of reserve should be best understood and whether it has interesting implications for understanding synaesthesia. Reserve is sometimes understood in terms of efficient domain-general resources that, for instance, sit outside of the core memory system. This might include executive functions that are used to deploy mnemonic strategies or inhibit irrelevant material (e.g., Buckner, 2004), processes which have themselves been linked to IQ (Duncan, 2010). Although we did not measure IQ, we deliberately used material that is less susceptible to mnemonic strategies. Moreover, we establish that education level had no significant effect on these particular tasks in Experiment 2. Although tangential to our main hypotheses, we also showed that musical expertise boosts memory for music but with no age X expertise interaction. In other words, having musical expertise improved memory for music in younger people, but did not mitigate against age-related differences.

Similarly then, synaesthesia and musical expertise may both enhance memory without increasing reserves to draw upon in aging.

Ageing and synaesthesia may affect some aspects of memory more than others. In Experiment 1, both the effects of synaesthesia and the effects of ageing were more pronounced when considering correct and confident memory judgments rather than memory accuracy per se. In other words, synaesthetes, and younger people, showed bigger advantages (over non-synaesthetes and older people respectively) when they were confident. This may reflect the operation of other mechanisms (relating to metacognition about one's own performance), or it may reflect a real difference in the strength and qualities of the underlying memories. Confidence (when accurate) is often regarded as a proxy for memory strength, whereas confidence per se (irrespective of accuracy) reflects a bias in responding (Macmillan & Creelman, 1991).

In Experiment 2, it was also notable that distractors in which the shape was changed (i.e. correct colour, correct location, wrong shape) showed a striking effect of ageing compared to other distractors. These stimuli were also unusual in that they showed no benefit of synaesthesia (as noted in Pritchard et al., 2013): i.e., synaesthetes and controls performed similarly (unlike in the other distractors). We cannot find a good explanation for this finding in prior literature nor within our own hypotheses, but it could be investigated further by determining whether the effect remains when stimuli are familiar shapes (triangle, star, etc.) and by exploring whether it remains when figure-grounding is reversed (i.e., when the background rather than shape is coloured). Ecker, Maybery, and Zimmer (2013) present an interesting working memory study showing how colour affects shape memory but only when colour is present in the figure and not background (they did not consider ageing). Synaesthetes may show a memory advantage for shape if the saliency of colour were diminished by presenting in the background.

Across two studies our results support independent effects of age and synaesthesia on memory. This is in-line with the 'maintain advantage' hypothesis in which synaesthetes remain superior to controls at all age-groups but are not spared the effects of decline in aging. If the effects of synaesthesia (enhancing memory) and ageing (impairing memory) are of a similar magnitude, and they do not interact with each other, then they effectively cancel each other out. Thus a researcher studying ageing who came across an elderly synaesthete - but hadn't thought to enquire about synaesthesia - might conclude that the participant had an unexpectedly youthful memory ability. This could lead to the incorrect conclusion that this person had been protected against the effects of age, when they almost certainly had started at an enhanced level to begin with. As such, one important aspect of the present research is to highlight the need for researchers to ask about the presence of synaesthesia in future aging research. Although synaesthesia is rare, it is not so rare as to be trivial. Based on prevalence estimates of synaesthesia (4.4%, Simner et al., 2006), there are presently 307 million synaesthetes worldwide, including 4.1 million elderly (65+ years) synaesthetes within the EU, and 2 million in the USA.

In summary, this research shows that synaesthesia enhances memory in later life as well as in younger people and that the independent but opposing effects on memory of synaesthesia and ageing (enhancing v. diminishing) mean that older synaesthetes can possess the memory abilities of average younger people.

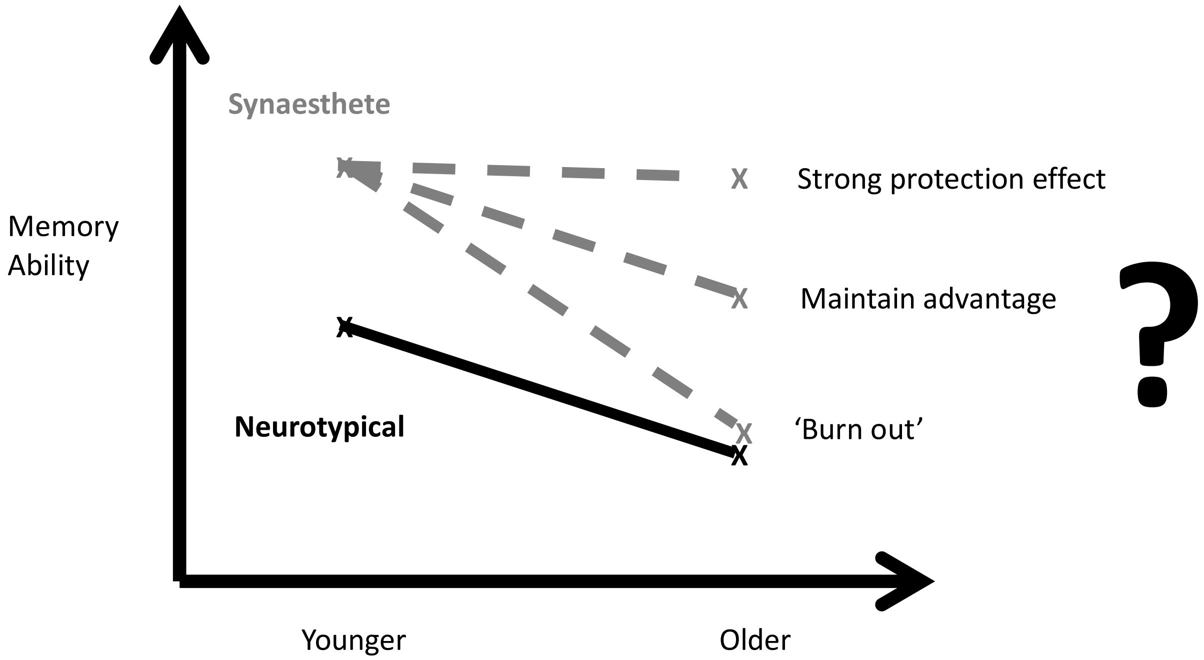

Figure 1. Schematic figure illustrating the known age-related differences in memory ability, and the known memory advantage of synaesthetes (in younger samples) with three possible levels of performance for older synaesthetes.

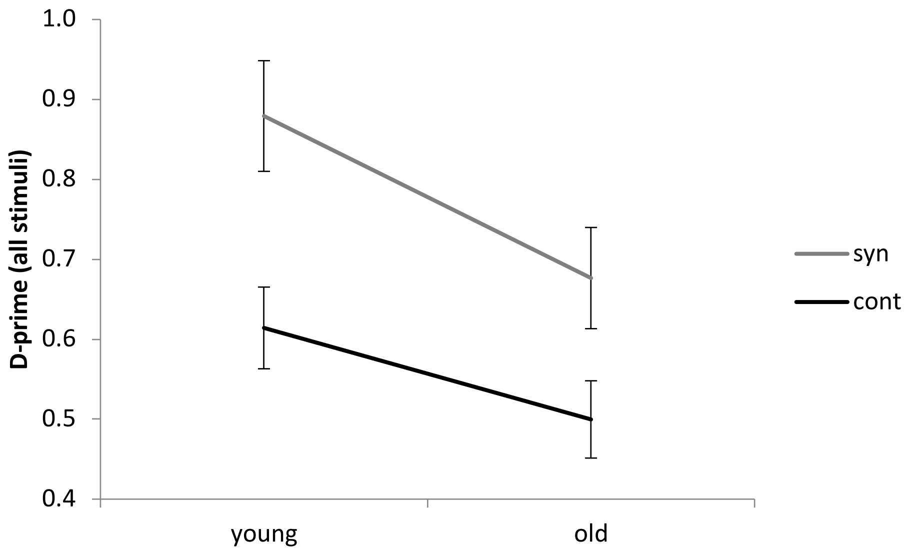

Figure 2. Performance of young and older synaesthetes and neurotypical controls for recognition memory (d-prime) for three kinds of stimuli. Error bars show +/- 1 SEM.

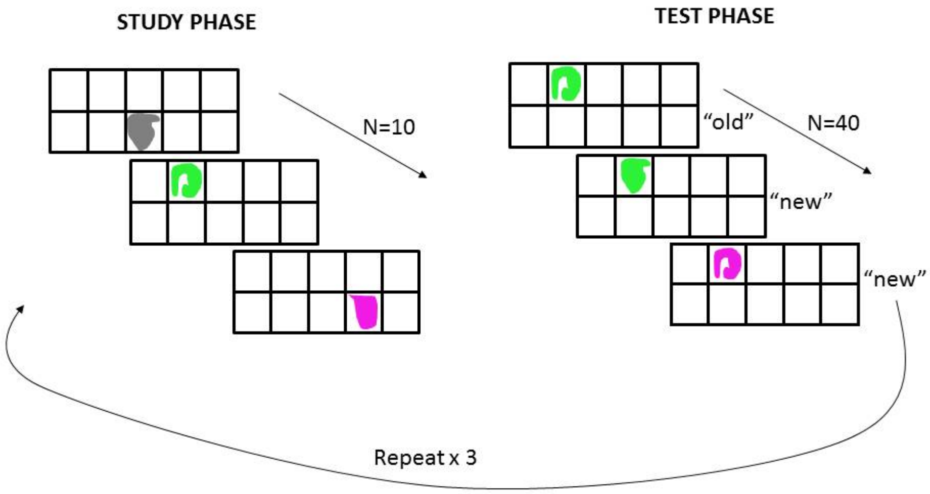

Figure 3: Trial diagram of Experiment 2. Participants learned ten colour-shape-location conjunctions during the learning phase. They were then classified target and distractor stimuli as old or new during the test phase.

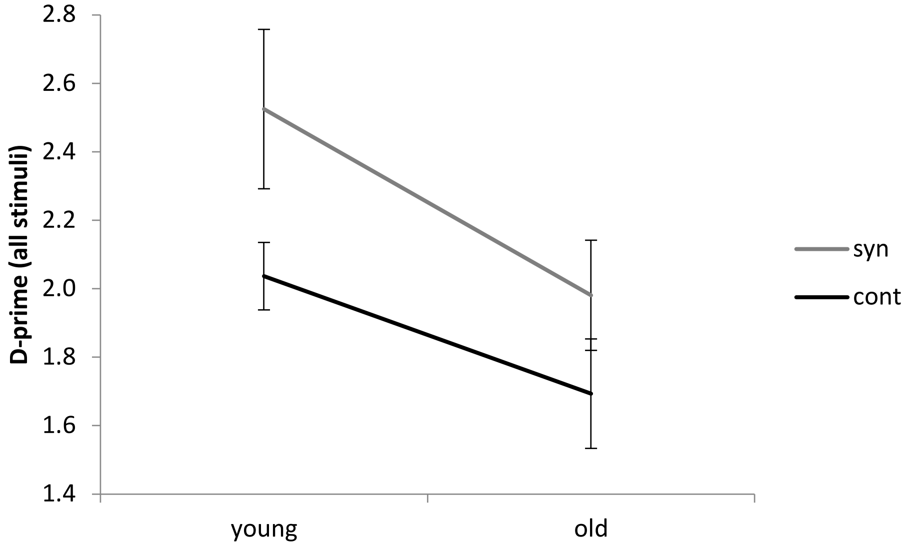

Figure 4: Overall performance (d-prime) In Experiment 2 as a function of age group and synaesthesia. Bars represent +/- 1 SEM.

Table 1. Demographic information for participants in Experiment 1

Age group	Synaesthete group	N	Age (SD)	% female	Musical experience		
					% little/none	% intermediate	% expert
Older	Synaesthete	17	64 (6.91)	100.0	33.3	33.3	33.3*
	Control	29	67 (6.09)	72.4	58.3	16.7	25
Younger	Synaesthete	22	23 (3.39)	77.3	31.8	31.8	36.4
	Control	30	23 (2.81)	66.7	30.0	43.3	26.7

* Information was unavailable for two participants

Table 2. Recognition memory accuracy for the three different kinds of stimuli, broken down by group. Bias is calculated as Criterion C.

	Digits (mean and SEM)		**Snowflakes (mean and SEM)**		**Music (mean and SEM)**		**Overall (mean and SEM)**	
	d-prime	bias	d-prime	bias	d-prime	bias	d-prime	bias
old syns	0.95 (0.11)	0.07 (0.11)	0.58 (0.08)	-0.08 (0.09)	0.50 (0.10)	0.05 (0.09)	0.69 (.07)	0.01 (.08)
old controls	0.70 (0.11)	-0.01 (0.07)	0.45 (0.05)	-0.03 (0.06)	0.35 (0.06)	0.08 (0.12)	0.50 (.05)	0.01 (.07)
young syns	0.88 (0.09)	-0.02 (0.05)	0.69 (0.08)	0.19 (0.05)	1.07 (0.08)	0.10 (0.05)	0.88 (.06)	0.09 (.04)
young controls	0.60 (0.08)	0.00 (0.04)	0.46 (0.06)	0.10 (0.04)	0.78 (0.08)	0.08 (0.05)	0.61 (.05)	0.06 (.03)

Table 3. Memory performance broken down by confidence and stimulus. Note that the tendency for older synaesthetes to be correct and confident more closely resembles that of younger non-synaesthetes (a youthful memory profile) than that of older non-synaesthetes.

	Digits (mean and SEM)		**Snowflakes (mean and SEM)**		**Music (mean and SEM)**	
	% Correct Confident	% Incorrect Confident	% Correct Confident	% Incorrect Confident	% Correct Confident	% Incorrect Confident
old syns	26.18 (2.83)	10.20 (1.46)	25.78 (3.42)	11.47 (2.29)	20.69 (3.30)	8.24 (1.46)
old controls	20.69 (2.72)	6.55 (1.13)	18.33 (1.74)	8.79 (1.32)	12.76 (1.86)	5.63 (1.09)
young syns	37.65 (2.94)	11.29 (2.45)	30.45 (3.08)	11.97 (2.01)	33.41 (2.64)	7.42 (1.14)
young controls	23.28 (2.12)	10.17 (1.24)	21.89 (2.01)	11.89 (1.67)	25.22 (2.34)	10.83 (1.65)

Table 4. Demographic information for participants in Experiment 2

Age group	Synaesthete group	N	Age (SD)	% female	Education		
					% level 1	% level 2	% level 3
Older	Synaesthete	18	65 (4.52)	100.0	33.3	22.2	44.5
	Control	21	67 (5.63)	76.2	14.3	38.1	47.6
Younger	Synaesthete	18	23 (3.01)	94.4	16.7	38.9	38.9*
	Control	84	22 (2.50)	72.6	11.9	57.1	31.0

*one participant's education data unavailable for this group

Table 5. Summary of performance in Experiment 2 broken down by type of stimulus

	Overall d-prime (mean,SD)	Overall Bias, Criterion C (mean,SD)	Overall (% correct, SEM)	Hits (%, SEM)	Colour FA (%, SEM)	Shape FA (%, SEM)	Location FA (%, SEM)
old syns	1.98 (.46)	-0.15 (.20)	82.1 (1.5)	85.5 (0.8)	19.4 (1.2)	37.8 (2.1)	9.1 (0.6)
old controls	1.69 (.73)	-0.05 (.16)	78.4 (2.0)	80.0 (0.9)	23.2 (1.1)	33.0 (1.6)	14.6 (0.9)
young syns	2.53 (.99)	0.09 (.20)	89.3 (1.8)	86.9 (1.0)	7.3 (0.6)	13.8 (1.1)	5.7 (0.5)
young controls	2.04 (.90)	0.15 (.23)	82.3 (1.2)	78.5 (0.7)	14.8 (0.5)	19.5 (0.7)	9.0 (0.5)

References

Asher, J. E., Lamb, J. A., Brocklebank, D., Cazier, J. B., Maestrini, E., Addis, L., . . . Monaco, A. P. (2009). A Whole-Genome Scan and Fine-Mapping Linkage Study of Auditory-Visual Synesthesia Reveals Evidence of Linkage to Chromosomes 2q24, 5q33, 6p12, and 12p12. American Journal of Human Genetics, 84(2), 279-285. doi: 10.1016/j.ajhg.2009.01.012

Barulli, D., & Stern, Y. (2013). Efficiency, capacity, compensation, maintenance, plasticity: emerging concepts in cognitive reserve. Trends in Cognitive Sciences, 17(10), 502-509. doi: 10.1016/j.tics.2013.08.012

Buckner, R. L. (2004). Memory and Executive Function in Aging and AD: Multiple Factors that Cause Decline and Reserve Factors that Compensate. Neuron, 44, 195-208

Dienes, Z. (2014). Using Bayes to get the most out of non-significant results. Frontiers in Psychology, 5, 781.

Duncan, J. (2010). The multiple-demand (MD) system of the primate brain: mental programs for intelligent behaviour. Trends in Cognitive Sciences, 14(4), 172-179. doi: 10.1016/j.tics.2010.01.004

Ecker, U. K. H., Maybery, M., & Zimmer, H. D. (2013). Binding of Intrinsic and Extrinsic Features in Working Memory. Journal of Experimental Psychology: General, 142(1), 218 –234

Finkel, D., Reynolds, C. A., McArdle, J. J., & Pedersen, N. L. (2005). The longitudinal relationship between processing speed and cognitive ability: Genetic and environmental influences. Behavior Genetics, 35(5), 535-549. doi: 10.1007/s10519-005-3281-5

Garrett, D. D., Grady, C. L., & Hasher, L. (2010). Everyday Memory Compensation: The Impact of Cognitive Reserve, Subjective Memory, and Stress. Psychology and Aging, 25(1), 74-83. doi: 10.1037/a0017726

Hall, C. B., Derby, C., LeValley, A., Katz, M. J., Verghese, J., & Lipton, R. B. (2007). Education delays accelerated decline on a memory test in persons who develop dementia. Neurology, 69(17), 1657-1664. doi: 10.1212/01.wnl.0000278163.82636.30

Hultsch, D. F., Hertzog, C., Small, B. J., & Dixon, R. A. (1999). Use it or lose it: Engaged lifestyle as a buffer of cognitive decline in aging? Psychology and Aging, 14(2), 245-263. doi: 10.1037//0882-7974.14.2.245

Jeffreys, H. (1961). *Theory of Probability*, 3rd ed. Oxford Classic Texts in the Physical Sciences. Oxford Univ. Press, Oxford.

Maguire, E. A., Valentine, E. R., Wilding, J. M., & Kapur, N. (2003). Routes to remembering: The brains behind superior memory. Nature Neuroscience, 6, 90-95.

Marchant, N. L., King, S. L., Tabet, N., & Rusted, J. M. (2010). Positive Effects of Cholinergic Stimulation Favor Young APOE epsilon 4 Carriers. Neuropsychopharmacology, 35(5), 1090-1096. doi: 10.1038/npp.2009.214

Macmillan, N., & Creelman, C. D. (1991). Detection theory: A user's guide. New York: Cambridge University Press.

Meier, B., Rothen, N., & Walter, S. (2014). Developmental aspects of synaesthesia across the adult lifespan. Frontiers in Human Neuroscience, 8. doi: 10.3389/fnhum.2014.00129

Nyberg, L., Lovden, M., Riklund, K., Lindenberger, U., & Backman, L. (2012). Memory aging and brain maintenance. Trends in Cognitive Sciences, 16(5), 292-305.

Persson, J., Pudas, S., Lind, J., Kauppi, K., Nilsson, L.-G., & Nyberg, L. (2012). Longitudinal Structure-Function Correlates in Elderly Reveal MTL Dysfunction with Cognitive Decline. Cerebral Cortex, 22(10), 2297-2304. doi: 10.1093/cercor/bhr306

Pritchard, J., Rothen, N., Coolbear, D., & Ward, J. (2013). Enhanced associative memory for colour (but not shape or location) in synaesthesia. Cognition, 127(2), 230-234. doi: 10.1016/j.cognition.2012.12.012

Ronnlund, M., Nyberg, L., Backman, L., & Nilsson, L. G. (2005). Stability, growth, and decline in adult life span development of declarative memory: Cross-sectional and longitudinal data from a population-based study. Psychology and Aging, 20(1), 3-18. doi: 10.1037/0882-7974.20.1.3

Rothen, N., & Meier, B. (2010). Grapheme-colour synaesthesia yields an ordinary rather than extraordinary memory advantage: Evidence from a group study. Memory, 18(3), 258-264. doi: 10.1080/09658210903527308

Rothen, N., Meier, B., & Ward, J. (2012). Enhanced memory: Insights from Synaesthesia. Neuroscience and Biobehavioral Review, 36(8), 1952-1963.

Rouw, R., & Scholte, H. S. (2007). Increased structural connectivity in grapheme-color synesthesia. Nature Neuroscience, 10, 792-797.

Rouw, R., & Scholte, H. S. (2010). Neural Basis of Individual Differences in Synesthetic Experiences. Journal of Neuroscience, 30(18), 6205-6213. doi: 10.1523/jneurosci.3444-09.2010

Satz, P. (1993). Brain reserve capacity on symptom onset after brain injury: A formulation and review of evidence for threshold theory. Neuropsychology, 7, 273–295.

Simner J., Glover L., & Mowat, A. (2006). Linguistic determinants of word colouring in grapheme-colour synaesthesia. Cortex, 42 281-289

Simner, J., Harrold, J., Creed, H., Monro, L., & Foulkes, L. (2009). Early detection markers for synaesthesia in childhood populations. Brain, 132, 57-64.

Simner, J., Mulvenna, C., Sagiv, N., Tsakanikos, E., Witherby, S. A., Fraser, C., . . . Ward, J. (2006). Synaesthesia: The prevalence of atypical cross-modal experiences. Perception, 35, 1024-1033.

Simner, J., Ipser, A., Smees, R., & Alvarez, J. (2017). Does synaesthesia age? Changes in the quality and consistency of synaesthetic associations. Neuropsychologia, 106, 407-416.

Stern, Y. (2009). Cognitive reserve. Neuropsychologia, 47, 2015–2028.

Ward, J. (2013). Synesthesia. Annual Review of Psychology, 64, 49-75.

Ward, J., Hovard, P., Jones, A., & Rothen, N. (2013). Enhanced recognition memory in grapheme-color synaesthesia for different categories of visual stimuli. Frontiers in psychology, 4. doi: 10.3389/fpsyg.2013.00762

Wiens, S. (2017). Aladins Bayes Factor in R. figshare 10.17045/sthlmuni.4981154

Weiss, P. H., & Fink, G. R. (2009). Grapheme-colour synaesthetes show increased grey matter volumes of parietal and fusiform cortex. Brain, 132, 65-70. doi: 10.1093/brain/awn304